Bayesian Ambient Noise Inversion for Geoacoustic Uncertainty Estimation

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LONG-TERM GOALS

Estimation of seabed geoacoustic parameters in shallow water by remote sensing remains a challenging task due to constraints on hardware, data collection and analysis, and cost of maritime surveys. This work focuses on the application of two techniques that might offer a solution to those constraints: the use of ambient noise to probe the seabed, and Bayesian inversion of these data to estimate geoacoustic parameters of interest together with their uncertainties. The long-term goal of this work is to establish general methods for processing and inverting ambient noise data and assessing the quality of the results by quantifying their uncertainties.

OBJECTIVES

This work has three main objectives: first, quantifying the ability to resolve seabed geoacoustic parameters using ambient noise measurements. Second, comparing those estimates to the ones

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obtained from active source inversion methods. Third, considering the effect of the resultant uncertainties for transmission loss and sonar performance prediction. A further objective related to this effort is increasing the understanding of the experimental conditions and equipment required for the collection of ambient noise data suitable for geoacoustic inversion.

APPROACH

Traditional investigation of seabed sediment properties has relied heavily on direct measurements such as core sampling/geo-probes, or indirect measurements with active systems. Direct methods have the evident problem of lack of spatial resolution due to time/cost constraints, while active methods can be limited due to deployment procedures and environmental concerns, often requiring the use of a vessel to tow the active device over a geographic area of interest. As an alternative to active systems, it has been shown that the wind-driven ambient noise field recorded at a vertical array carries information of the seabed layering structure[1] which is exploited in this research project. The technical approach for this work is as follows:

1) Selection of inversion method: the Bayesian framework has been selected in this study to carry out geoacoustic inversion from ambient noise data. In the Bayesian method[2], each parameter m_i of the model vector **m** (parameters include seabed layer thicknesses, sound speeds, densities, and attenuations, as well as noise variances at each frequency) is included as a random variable with an assigned *prior probability distribution* $P(m_i)$ that represents what is known about m_i before the experimental data are available. As an example, if the only information available *a priori* is the range of possible values of m_i, then $P(m_i)$ can be assumed as to be a bounded uniform distribution, and the inversion algorithm applies the experimental data **d** to update the prior to the *posterior probability density* (PPD), $P(\mathbf{m}|\mathbf{d})$ from which quantities of interest such as parameter marginal distributions, correlations and variances can be obtained. The link between prior and posterior distributions is the *likelihood function* $L(\mathbf{d}|\mathbf{m})$, and techniques for choosing this function have been well documented[2]. The work by Dosso and Dettmer at the University of Victoria (in collaboration with Charles Holland of Pennsylvania State University) on Bayesian controlled-source reflection coefficient inversion is directly applicable to the proposed inversion of similar data as extracted from the ambient noise field. The UVic group has developed efficient parallel algorithms for geoacoustic parameter estimation and uncertainty analysis which form the starting point of the ambient noise inversion reported here.

2) Implementation of software routines for numerical estimation of the PPD: Since analytical solutions for the PPD are generally not available for non-linear problems, Markov chain Monte Carlo (MCMC) methods can be used to sample from this distribution[2]. In this work, optimization algorithms such as adaptive simplex simulated annealing can be used to determine the maximum *a posteriori* (MAP) model. Metropolis-Hastings sampling[3] (MHS) is applied to determine marginal probability densities. In both cases, perturbations are applied in a principal-component parameter space, which is a rotated representation of the physical parameter space in which the axes align with the dominant correlation directions. This rotation provides a more efficient exploration of the parameter space, and is particularly effective when strong correlations between parameters are present.

3) Identification and validation of a forward model: the input to the Bayesian inversion is the bottom loss (BL), which can be computed from the ratio of upward to downward energy fluxes obtained by beamforming ambient noise measured at a VLA[4,5]. The forward model consists of a representation of the ambient noise data covariance matrix, from which replicas of the BL can be

estimated for different combinations of the geoacoustic parameters. This replica BL is adjusted to include the smearing effect introduced by the VLA's finite aperture. Software routines for the forward model can be validated by comparison with OASN, the ambient noise module from the wavenumber-integration model OASES[6] (OASN itself is computationally expensive to use in the inversion algorithm).

4) Synthetic data obtained from the forward model are used for investigating the effect of array design and experimental conditions (wind speed, spatial correlation of the wind-driven noise, angular distribution) which will provide further understanding of the environmental conditions required to perform successful inversions, as quantified by geoacoustic uncertainties.

5) Experimental datasets from previous publications[7] are available through Martin Siderius for testing the Bayesian approach. These datasets have the advantage that considerable work has already been carried out regarding beamforming and conversion of reflection data into time series representing seabed profiles. Access to new data collections of ambient noise is also possible from collaboration with the NEAR-Lab.

WORK COMPLETED

1) The ray-tracing representation of the ambient noise field developed by Harrison[4] has been adopted in this work. This approach considers wind-driven surface dipoles as the driving mechanism for the ambient noise. The strength of this field relative to other unwanted noise mechanisms defines a signal-to-noise ratio (SNR), which is included in this work as a frequency-dependent parameter and it is shown to have a strong impact on the resolution of seabed geoacoustic parameters. This impact is quantified by marginal probability distributions from Bayesian inversion of simulated and experimental data.

2) The Bayesian inversion method has been applied to simulated data with varying SNR levels, and uncertainties of the estimated parameters as a function of sediment depth and SNR have been quantified for a realistic environment.

3) The Bayesian method was also applied to experimental data provided by Martin Siderius from the MAPEX2000bis experiment[7], using a moored array located in a well surveyed region. The estimated geoacoustic parameters were compared to results from previous work[8] using active-source methods and direct (core samples) methods, showing good agreement.

RESULTS

The following results show the application of the Bayesian inversion framework to simulated data, which highlights the importance of considering the SNR as an unknown frequency-dependent parameter. The inversion technique is also applied to experimental data and compared to previous results obtained by inversion of active-source data as well as core samples from a nearby region.

Study of geoacoustic resolution using simulated data:
Simulated ambient noise data were generated from the forward model using the environment described in Table 1. The water column is 130-m deep and the receiving array has 32 elements spaced by 0.5 m from 88–104 m depth. This setting mimics the experimental conditions during the MAPEX2000bis experiment[7], described in the next sub-section. The frequency-dependent source strength was

computed as[9] $Q(f) = 44.58 + (0.14) f 0.37\ V_s$, where V_s is the surface wind speed in knots and f is the frequency in hertz. Wind speeds of 5, 10 and 15 kts were considered to quantify the effect of SNR on geoacoustic resolution.

Table 1: Sound speed (c), density (ρ), attenuation (α), and layer thickness (h) for the five-layer model used to generate simulated data.

	Parameters			
Layer	***c* (m/s)**	***ρ* (kg/m3)**	***α* (dB/λ)**	***h* (m)**
1	1525	1400	0.09	0.89
2	1707	2257	1.28	0.39
3	1668	1779	0.54	0.49
4	1532	1559	0.35	0.55
5	1466	1405	0.13	halfspace

The variation in information content with wind speed can be observed from the marginal probability profiles in Figure 1, obtained from MCMC sampling of the PPD. The parameters of the top layer are in good agreement with the true model even in the worst case of low wind speed (Figure 1(c)). Deeper layers are well resolved for wind speed of 10 and 15 kts, for which the SNR is greater than 0 dB at all frequencies. However, at 5 kts all SNRs are lower than −5 dB, resulting in loss of geoacoustic resolution for all parameters. In Figure 1(a) the marginal PPDs for sound speeds and thicknesses are compact, indicating good geoacoustic resolution. On the other hand, the support of the PPDs for densities and attenuations tends to fill a greater proportion of their prior distributions. This behaviour can be explained from the frequency-angle structure of the bottom loss, in which the ratio between layer thickness and sound speed determines the location of periodic fringes. The attenuation and the density remain as parameters that mostly influence the energy level, which is a weaker feature of the bottom loss.

Geoacoustic inversion using experimental data:

Ambient noise data were collected on November 22nd during the MAPEX 2000 experiment[7], carried out on the Malta Plateau using a moored VLA located at (36.44357 N lat., 14.77618 E long.). During the experiment, ambient noise was recorded at a sampling rate of 6000 Hz with an 80-element array consisting of three sub-arrays. The data used in this work correspond to the middle sub-array with 32 equally-spaced elements spanning 88-104 m depth.

With experimental data, the number of layers to be included in the forward model is an unknown. In this work, the Bayesian information criterion[2] (BIC) is used to determine the optimal seabed parameterization, resulting in a model with 5 layers (including the halfspace). Figure 2 (a) shows the fit to the experimental data for the 5-layer MAP model at frequencies 635 Hz, 800 Hz, 1008 Hz, 1270 Hz, and 1400 Hz. Using the MAP model obtained from measured data, the bottom loss was also computed at frequencies from 600–1600 Hz and angles from 0^{o} –90^{o}, as a test of the capability of the MAP model to match data at frequencies and angles other than those used for the inversion. The result is presented in Figure 2 (b) compared to the experimental bottom loss, and both plots share similar characteristics in the critical angle, location of the main fringes, and loss levels.

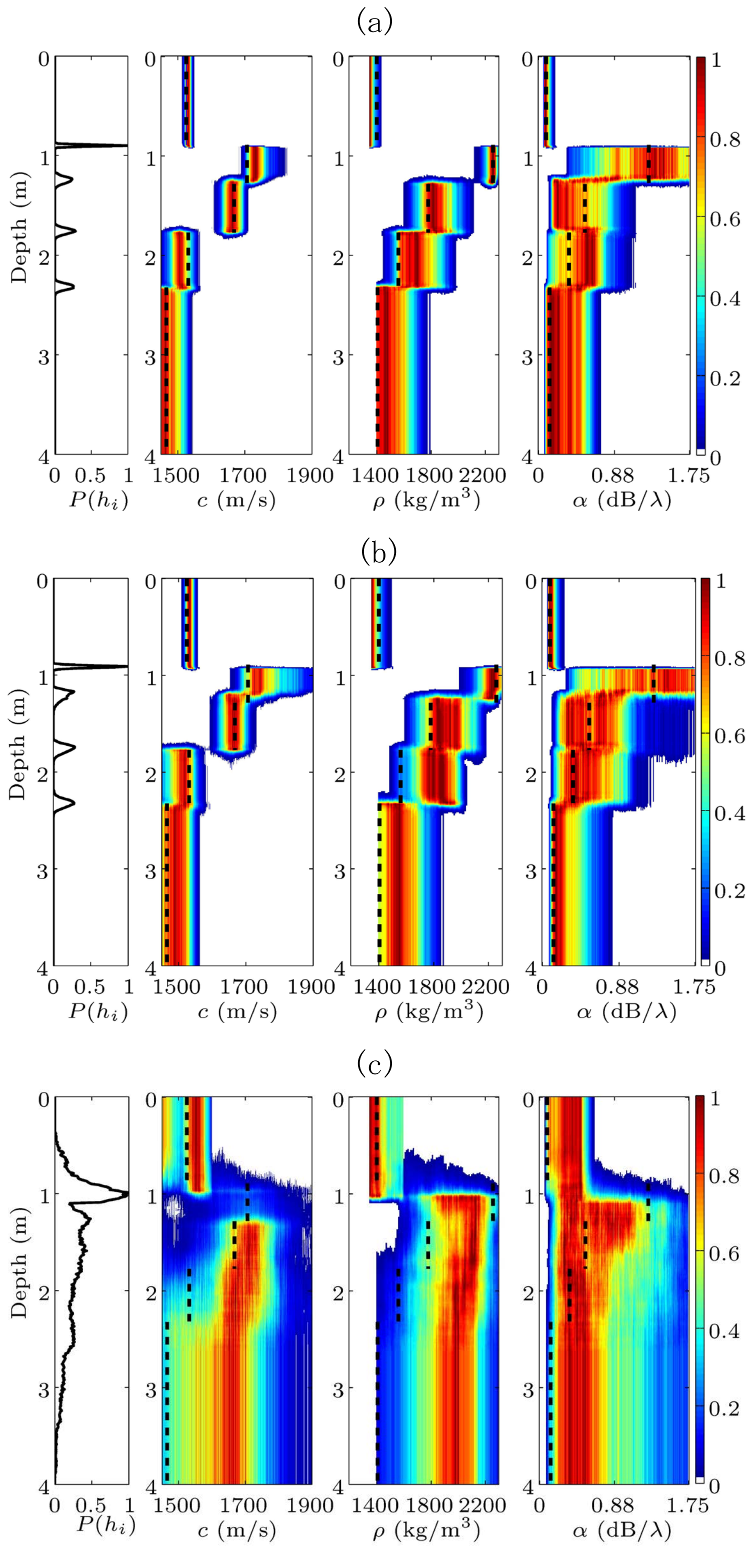

Figure 1: Marginal probability profiles for the layer thickness, sound speed, density, and attenuation obtained from simulated data with: (a) V_s =15 kts, (b)V_s=10 kts and (c) V_s = 5 kts. Dashed lines indicate the true model from Table 1. The profiles are normalized to have a maximum of 1; profiles for c, ρ and α are normalized independently at each depth. Figures from Quijano et al.[10].

The marginal probability profiles from Bayesian inversion of the data are shown in Figure 3(a). These PPDs resemble the results from the simulated inversion with *Vs* = 15 kts in [Figure 1(a)]: all geoacoustic parameters are well determined over the top layer, and then the distributions widen with depth, particularly for density and attenuation. In Figure 3(a), measurements of the sound speed and the density from core samples from a nearby area are plotted overlying the probability profile. The marginal PPDs for sound speed and density are in good agreement with the corresponding cores to 0.9 m depth for the sound speed (total core depth) and to 1.5 m depth for the density. Beyond this depth, the estimated density decreases but the core measurement remains at a value ~2100 kg/m^3. This disagreement in the density is also observed in a profile obtained by Bayesian inversion of active-source spherical reflection coefficient data from Dettmer et al.[8], shown in Figure 3(b). This suggests a possible problem with the core sample (e.g., compaction of the lower part of the core) since both inversion profiles were obtained from independent acoustic measurement methods.

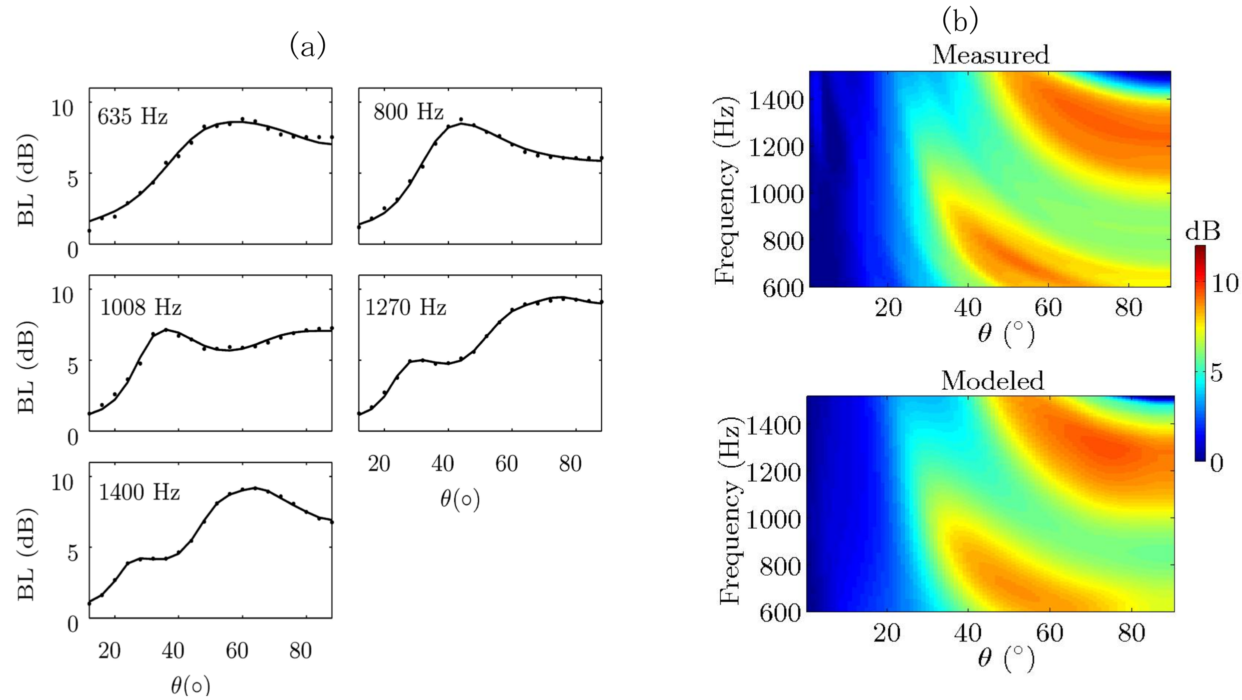

Figure 2: (a) Experimental BL (dots) compared to the predicted BL data evaluated at m_{MAP} (solid lines) at the five frequencies used for inversion; (b) BL computed from measured data (top) and from the forward model evaluated at m_{MAP} (bottom). Figures from Quijano et al.[10].

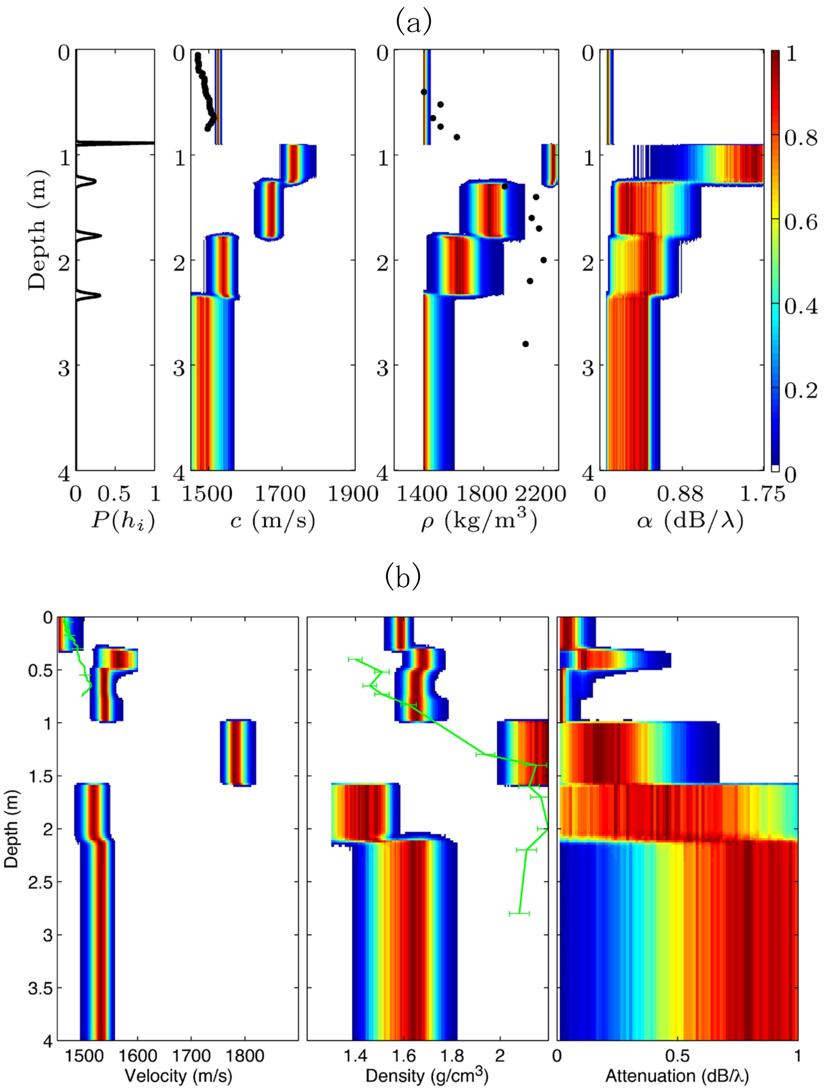

Figure 3: (a) Marginal probability profiles from the experimental bottom loss inversion. The black dots are sound speed and density core measurements taken at a location ~400 m away from the array (figure from Quijano et al.[10]); (b) Similar profile from Dettmer et al.[8] obtained by active-source methods; green symbols and lines indicate core measurements.

The importance of considering SNR in ambient noise inversion can be quantified by study of parameter correlations. Figure 4 shows the correlation coefficient matrices for the inversion of measured data and simulated data with V_s = 15 kts. In both cases there is significant correlation between the SNRs at different frequencies and between SNR and layer thicknesses, sound speeds and densities, while the correlations between SNR and attenuations are weaker in both simulated and experimental cases. It is interesting to see similar correlation patterns when comparing the modeled (V_s = 15 kts) and the measured cases, in particular those involving parameters of layer 1 as well as the correlations between SNRs.

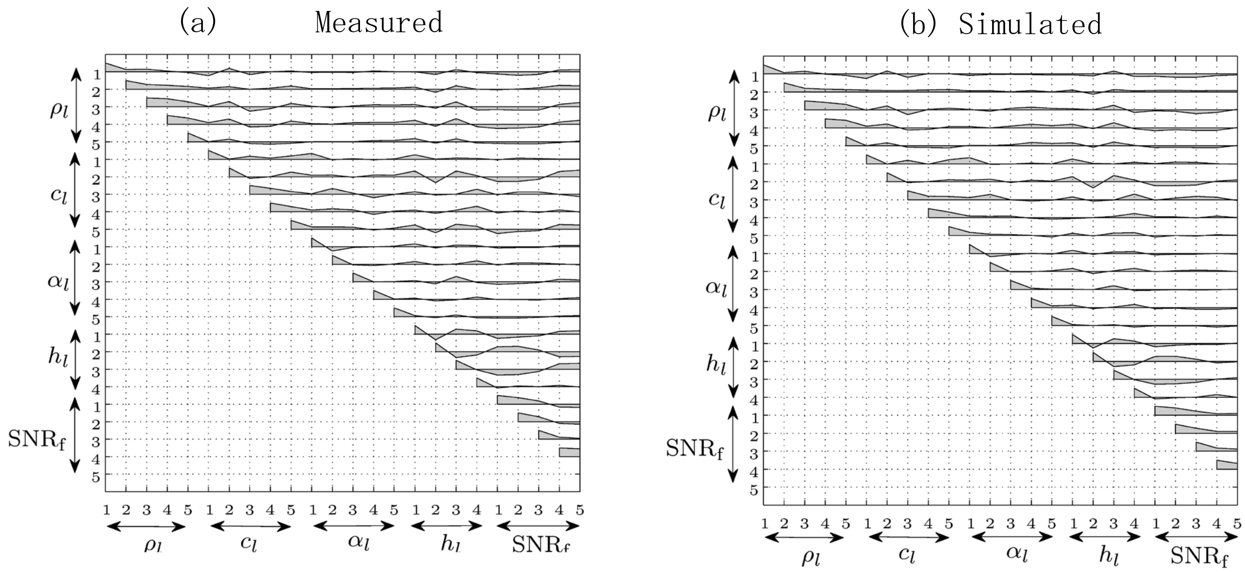

Figure 4: Parameter correlation matrices from the inversion of (a) measured and (b) simulated data, with wind speeds of ~20–22 and 15 kts, respectively. For simplicity, only the upper triangle of the symmetric matrix is plotted. Figures from Quijano et al.[10].

Examination of joint marginal PPDs in Figure 5 also reveals strong dependencies between parameters. In this figure, the left column shows the marginals derived from the Bayesian inversion of the experimental data, while the right column corresponds to similar results obtained from the simulated data at V_s = 15 kts. The exact values of the SNRs may be difficult to match between experiment and simulation, since the true level of isotropic noise is unknown in the experimental data. Nevertheless, these joint PPDs demonstrate that fixing the SNR to an arbitrary value or assuming infinite SNR could result in biased estimates of the geoacoustic parameters.

IMPACT/APPLICATIONS

In shallow water regions the performance of Navy sonar systems is strongly influenced by acoustic interaction with the seabed and therefore, knowledge of geoacoustic parameters and their corresponding uncertainties is required to predict and optimize sonar performance. Bayesian inversion methods offer an elegant and powerful framework not only for parameter extraction but also for uncertainty estimation, thereby quantifying the geoacoustic information content of the data. The proposed inversion methodology has been highly effective when applied to active surveys, and current results using experimental and simulated ambient noise data show a lot of potential to overcome limitations of current methods of geoacoustic inversion.

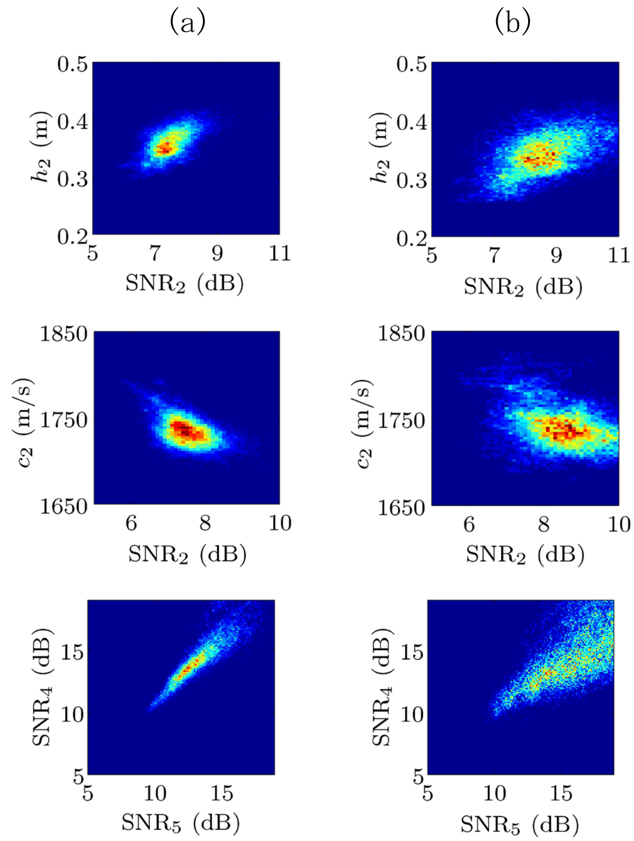

Figure 5 Selected joint marginal PPDs derived from the Bayesian inversion of: (a) the experimental data and (b) the simulated data at V_s = 15 kts. Figures from Quijano et al.[10].

RELATED PROJECTS

1) Bayesian Seismo-Acoustic Inversion to Investigate Spatial Variability and Uncertainty of Shallow Water Sediments, 2007-2008 (Award Number: N000140710540). This project developed software tools that implement Bayesian inversions for sediment sound speed, density and attenuations from seismo-acoustic data collected with an active source, and quantifies the uncertainties of the estimated parameters. The proposed work develops similar approaches for ambient noise data. This will determine the sensitivity of the estimates for different seabed parameters, as well as improving understanding of ambient noise structure and processing from synthetic and experimental data.

2) High Frequency Acoustic Channel Characterization for Propagation and Ambient Noise, 2006-2010 (Award Number: N00014-05-C-0116). This research has had impact on several experimental and theoretical aspects of ambient noise data collection: array design, usable frequency band, deployment techniques, beamforming processing, models for the generation of ambient noise, and inversions using genetic algorithm approaches.

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PUBLICATIONS

[1] J. E. Quijano, S. E. Dosso, J. Dettmer, L. M. Zurk, M. Siderius, and C. H. Harrison, Bayesian geoacoustic inversion using wind-driven ambient noise, submitted to J. Acoust. Soc. Am, 2011.